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ENCOUNTER PROBABILITIES FOR AVALANCHE DAMAGE

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A common problem in selecting sites for mountain construction or development is determining the probability of avalanche damage. Prudent planning dictates that sites should be completely free of avalanche danger if at all possible. This should be the inflexible standard for buildings and lodges in recreation developments, but a slight exposure to avalanche hazard is sometimes acceptable for ski lifts or parking areas. In the case of mining construction or other industrial enterprises where the character of hazard exposure can be more strictly controlled, a more substantial risk of damage may sometimes be acceptable. This risk is known as encounter probability.

The problem normally is not posed by large avalanches which run frequently (annually or oftener). These present such obvious prospects of repeated damage and destruction that they must either be avoided entirely or else defended or eliminated by what may be prohibitively expensive construction. More often a proposed site lies within or adjacent to a slide path where normal avalanche activity is limited and non-destructive, but which shows evidence of infrequent avalanches of potentially destructive proportions.

The situation is similar to that posed by other geophysical hazards---earthquakes, floods, tidal waves, hurricanes---which recur in destructive size at long and irregular intervals. The concept of a "20-year flood" or "100-year flood" is familiar to the hydrologic engineer. The avalanche specialist is faced with the similar problem of evaluating prospective damage from a "20-year avalanche" or a "100-year avalanche". It often is undesirable or too costly to avoid completely the prospects of damage from an avalanche which may fail only once a century. In some circumstances, such as the exposure of a large number of people, the only acceptable hazard may be zero and there is

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no choice but to seek another and safer location. There sometimes is economic justification for accepting a limited amount of risk for buildings or other installation, especially mining or other enterprises where a definite and limited building life can be projected. Such risks can logically be taken only if their size can be reasonably estimated. This report presents methods for naking such estimates, or encounter probability.

Large, infrequent avalanches, like large, infrequent river floods, are the roduct of unforseeable weather and climate. For purposes of statistical analysis they are considered to occur at random even though there may be some evidence for their association with short-term (in the geologic sense) climate cycles. The *average* time between a number of such random events is called the *return interval*. For the kind of avalanches under discussion, typical return intervals night be 25, 50 or 100 years. Most installations are designed for a useful *stimated life* which depends on such factors as economics, construction materials nd rate of obsolescence. When such an installation is exposed for its estinated life to the threat of damage from an infrequent avalanche of a given eturn interval, there is a definite *encounter probability* which describes the hance that the avalanche will damage the installation during its estimated life.

Table 1 and 2 enumerate these encounter probabilities for the given values f return interval and estimated life. They are derived from a paper by Borgman 1) which treats the subject of geophysical risks in considerable depth. The esign engineer seeking a more sophisticated treatment is referred to this paper.

In using these tables, it is important to consider the restrictions imposed n their construction. First, and in general, statistics treat the relations etween numbers or groups of numbers. These relations may or may not describe

hysical reality. They predict probable consequences but do not assign causes. econd, both tables are based on the assumption that occurrences of the event n question (in this case major avalanches) are random and independent. This eans that the encounter probability does not change because the event occurs. his is another way of stating the gambler's maxim: "The laws of chance have o memory."

Table 1 is calculated on the assumption that the events occur only at ntegers on the time scale. This may seem an arbitrary and impractical estriction, but in the case of avalanche hazard it has some useful applications. f most avalanches of a damaging size are known to occur at a given site in, ay, January, then such events will fall close to the time scale integers if he convenient time unit of a year is chosen.

Table 2 removes this restriction, allowing the events to occur at any point n the time scale. The following mathematical restrictions, however, have een observed in calculating Table 2: The process is stationary, possesses ndependent increments, and has a time-independent average. Two or more events annot occur simultaneously.

Allowing the events to occur at any point on the time scale gives a more ealistic flexibility to the calculations, but does raise another problem when ealing with avalanches in time units of years. Avalanches do not occur at ny point on such a time scale; they occur only in the winter. This difficulty ay be circumvented if the chosen time unit is winter months for both the return nterval and the estimated life. The estimate of encounter probability is then ased on a continuous time scale made up of years consisting of those four or ve winter months when avalanche damage is possible. The balance of each year

when avalanche occurrence is zero is ignored along with that same portion of the estimated life.

Note that for long return intervals and low encounter probabilities the two Tables give very similar or identical figures.

TABLE 1.-ENCOUNTER PROBABILITY, E_1, VERSUS ESTIMATED LIFE, L, AND RETURN PERIOD $\overline{T}_1$. $\left[E_1=1-\left(1-\frac{1}{\overline{T}_1}\right)^L\right]$

$\overline{T}_1$	5	10	15	20	25	30	40	50	60
1	0.200	0.100	0.067	0.050	0.040	0.033	0.025	0.020	0.017
2	0.360	0.190	0.129	0.098	0.078	0.066	0.049	0.040	0.033
3	0.488	0.271	0.187	0.143	0.115	0.097	0.073	0.059	0.049
4	0.590	0.344	0.241	0.185	0.151	0.127	0.096	0.078	0.065
5	0.672	0.410	0.292	0.226	0.185	0.156	0.119	0.096	0.081
6	0.738	0.469	0.339	0.265	0.217	0.184	0.141	0.114	0.096
7	0.790	0.522	0.383	0.302	0.249	0.211	0.162	0.132	0.111
8	0.832	0.570	0.424	0.337	0.279	0.238	0.183	0.149	0.126
9	0.866	0.613	0.463	0.370	0.307	0.263	0.204	0.166	0.140
0	0.893	0.651	0.498	0.401	0.335	0.288	0.224	0.183	0.155
2	0.931	0.718	0.563	0.460	0.387	0.334	0.262	0.215	0.183
4	0.956	0.771	0.619	0.512	0.435	0.378	0.298	0.246	0.210
6	0.972	0.815	0.668	0.560	0.480	0.419	0.333	0.276	0.236
8	0.982	0.850	0.711	0.603	0.520	0.457	0.366	0.305	0.261
0	0.988	0.878	0.748	0.642	0.558	0.492	0.397	0.332	0.285
5	0.996	0.928	0.822	0.723	0.640	0.572	0.469	0.397	0.343
0	0.999	0.958	0.874	0.785	0.706	0.638	0.532	0.455	0.396
5	0.999+	0.975	0.911	0.834	0.760	0.695	0.588	0.507	0.445
0	0.999+	0.985	0.937	0.871	0.805	0.742	0.637	0.554	0.489
5	0.999+	0.991	0.955	0.901	0.841	0.782	0.680	0.597	0.531
0	0.999+	0.955	0.968	0.923	0.870	0.816	0.718	0.636	0.568

	80	100	120	160	200	250	300	400	500
1	0.012	0.010	0.008	0.006	0.005	0.004	0.003	0.002	0.002
2	0.025	0.020	0.017	0.012	0.010	0.008	0.007	0.005	0.004
3	0.037	0.030	0.025	0.019	0.015	0.012	0.010	0.007	0.006
4	0.049	0.039	0.033	0.025	0.020	0.016	0.013	0.010	0.008
5	0.061	0.049	0.041	0.031	0.025	0.020	0.017	0.012	0.010
6	0.073	0.059	0.049	0.037	0.030	0.024	0.020	0.015	0.012
7	0.084	0.068	0.057	0.043	0.034	0.028	0.023	0.017	0.014
8	0.096	0.077	0.065	0.049	0.039	0.032	0.026	0.020	0.016
9	0.107	0.086	0.073	0.055	0.044	0.035	0.030	0.022	0.018
0	0.118	0.096	0.080	0.061	0.049	0.039	0.033	0.025	0.020
2	0.140	0.114	0.096	0.072	0.058	0.047	0.039	0.030	0.024
4	0.161	0.131	0.111	0.084	0.068	0.055	0.046	0.034	0.028
6	0.182	0.149	0.125	0.095	0.077	0.062	0.052	0.039	0.032
8	0.203	0.165	0.140	0.107	0.086	0.070	0.058	0.044	0.035
0	0.222	0.182	0.154	0.118	0.095	0.077	0.065	0.049	0.039
5	0.270	0.222	0.189	0.145	0.118	0.095	0.080	0.061	0.049
0	0.314	0.260	0.222	0.171	0.140	0.113	0.095	0.072	0.058
5	0.356	0.297	0.254	0.197	0.161	0.131	0.110	0.084	0.068
0	0.395	0.331	0.284	0.222	0.182	0.148	0.125	0.095	0.077
5	0.432	0.364	0.314	0.246	0.202	0.165	0.140	0.107	0.086
0	0.467	0.395	0.342	0.269	0.222	0.182	0.154	0.118	0.095

TABLE 2.-ENCOUNTER PROBABILITY, E_2, VERSUS ESTIMATED LIFE, L, AND RETURN PERIOD $\bar{T}_2$. $\left[E_2=1-e^{-L/\bar{T}_2}\right]$

$\bar{T}_2$	5	10	15	20	30	40	50	60	80	100	120	160	200	250	300	400	500
1	0.182	0.095	0.065	0.049	---	---	---	---	---	---	---	---	---	---	---	---	---
3	0.450	0.260	0.182	0.140	0.095	0.072	0.050	---	---	---	---	---	---	---	---	---	---
5	0.632	0.394	0.284	0.221	0.154	0.118	0.095	0.080	0.061	---	---	---	---	---	---	---	---
10	0.865	0.632	0.486	0.394	0.284	0.221	0.182	0.154	0.118	0.095	---	---	---	---	---	---	---
20	0.982	0.865	0.736	0.632	0.486	0.394	0.330	0.284	0.221	---	---	---	---	---	---	---	---
30	0.997	0.950	0.865	0.776	0.632	0.528	0.450	0.394	0.313	---	---	---	---	---	---	---	---
40	0.999	0.982	0.930	0.865	0.736	0.632	0.550	0.486	0.394	0.330	---	---	---	---	---	---	---
60	0.999+	0.997	0.982	0.950	0.865	0.776	0.700	0.632	0.528	0.450	0.394	0.313	0.260	0.214	0.182	0.139	0.113
80	0.999+	0.999+	0.995	0.982	0.931	0.865	0.799	0.736	0.632	0.550	0.486	0.394	0.330	0.274	0.235	0.182	0.148
00	0.999+	0.999+	0.999	0.993	0.964	0.918	0.865	0.812	0.714	0.632	0.566	0.415	0.394	0.330	0.284	0.221	0.182
20	0.999+	0.999+	0.999+	0.997	0.982	0.950	0.909	0.865	0.776	0.699	0.632	0.528	0.450	0.381	0.330	0.260	0.214
60	0.999+	0.999+	0.999+	0.999+	0.995	0.982	0.959	0.931	0.865	0.799	0.736	0.632	0.550	0.473	0.414	0.330	0.274
00	0.999+	0.999+	0.999+	0.999+	0.999	0.993	0.982	0.964	0.918	0.865	0.812	0.714	0.632	0.550	0.486	0.394	0.330
50	0.999+	0.999+	0.999+	0.999+	0.999+	0.998	0.993	0.982	0.956	0.918	0.875	0.790	0.714	0.632	0.516	0.465	0.394

Where the spaces are filled by a dash (-), the value is the same as in Table 1.

The biggest difficulty in applying these figures to evaluation of avalanche azard is determining average values of return intervals. The historical record n North America simply is not long enough to provide data from which averages an be calculated for avalanche return intervals greater than two or three ecades. The data that are available for a given avalanche path, whether from istorical records or inferred from indirect evidence, usually give at best the ength of a single return interval. In many cases there is evidence of a major valanche at some time in the past which has not recurred since. Evidence from ree growth can usually establish when the avalanche last fell, so all that is hen known is a minimum possible length of a single return interval. If this s all there is to go on, it will have to serve. But encounter probabilities ased on uncertain return intervals obviously will themselves be uncertain. xperienced judgment on the part of the avalanche specialist can take into account errain, climate and character of the avalanche path, thus placing the estimate f return intervals on a better basis than guesswork. Such improvement in ccuracy is real and often considerable, but it is essentially subjective and hus difficult to account for in statistical analysis.

This approach to estimating risks from avalanche hazard does not offer dvice on whether risks should be taken. This question is properly one to be nswered by administrative or operational decision. What is available is a ational method of determining just what the risk might be. The decision of hether to assume it can then proceed on a sounder basis.

xample No. 1

An avalanche of unusual size destroyed five houses at Twin Lakes, Colorado, n 1962. Historical records showed that a previous avalanche of this size had allen at this site in 1882. The houses had been constructed in the avalanche

ath during the interim, three of them quite recently. The average age of the ther two at the time of destruction was about 40 years. To what risk had they een exposed?

Here the return interval and estimated life are sufficiently long that there s very little difference between the figures given by Table 1 and 2. Lacking n average, we must use instead the single return interval of 80 years. Judgng from climate and terrain, this is a reasonable approximation. The time nit is years and the estimated (in this case actual) life is 40 years. From ble 1 the encounter probability is 0.395. The two older houses experienced pproximately two chances out of five of destruction. If their normal life nyway is 40 years, they were exposed to this *same encounter probability from e day they were built*, although the figures would not have been available to lculate it at that time. These figures tell, in other words, that they xperienced quite a good chance of eventual destruction at this site.

xample No. 2

Construction of a major ski development has been proposed in an area of nown avalanche activity. For the purpose of utilizing available private real tate, the developers wish to locate the main center of lodges, ski shops and her buildings adjacent to two major avalanche paths. Historical records ow that avalanches large enough to cause damage to the proposed development ll at this site in 1878, 1880, 1906 and 1955. Others may have fallen between 06 and 1955, but there are no records.

Return intervals from the available data are 2, 26 and 49 years. The erage is 25-2/3 years. Estimated life of the development is 25 years.

In this case it would be more realistic to use Table 2, with winter avalanche nths as the time unit. Snow data from this area suggest that the four months January through April are the time of principal avalanche danger. For the rpose of analysis, each year consists of these four months. To the nearest le months, the return interval is 103 months and the estimated life 100 months. tering Table 2 at the nearest round numbers for these values, the encounter obability is found to be 0.632. Chances are thus better than six out of ten at the ski area center will experience at least some avalanche damage during s life.

Such chances are quite unacceptable for facilities intended to house and tertain large numbers of visitors and the use of such a site must be rejected.

The real chance of damage is actually greater than that indicated by Table Because part of the record is missing, the return interval may actually be orter. Because two separate avalanche paths are involved, there is a chance at the same unusual snow and weather conditions which could create a damaging alanche on one could also create a damaging avalanche on the other. Thus ere is a possibility of two non-independent events, which violates one of e restrictions on Table 2. But the Table still gives at least the general gnitude of the risk.

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